Enhanced Maneuverability and Stability of Missiles

Presented To

3rd Annual Missiles and Rockets Symposium

April 19, 2002

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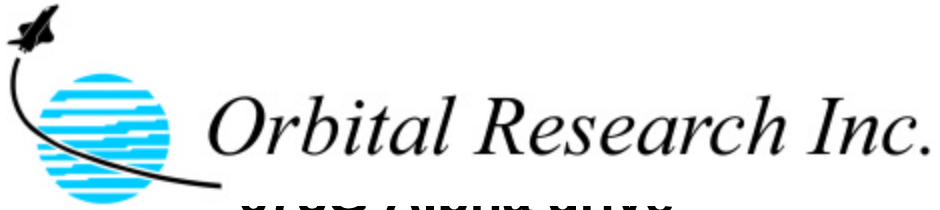

[illegible] Alpha drive

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Funding through — Air Vehicles Directorate, WPAFB, SBIR Program

Outline

- Orbital Research Background
  - Company History
  - Programs
- Active Flow Control Program Research
- Missile Stability and Maneuverability Enhancement
  - Vorticity Control Theory
  - Hardware and Experimental Set-up
  - Dynamic Test Results in Wind Tunnel
  - Conclusions

Company Background

- **Founded:** February, 1991
- **Mission:** To find new and innovative technological solutions in advanced controls and microdevices for various military and commercial applications.
- **Focus:** To transition basic research and development technologies from the laboratory environment to hardware platforms.
- **Location:** 673G Alpha Drive, Cleveland, Ohio
- **Employees**: Twenty employees (sixteen full-time) and twelve consultants
- **Core technologies:**
  - Micro Devices and Sensors
  - Advanced Controls

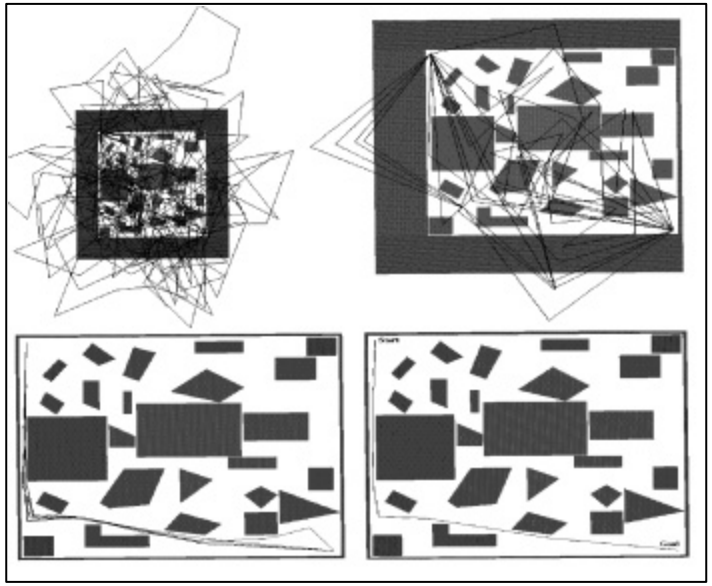
Orbital Research is a Small Business but….

- **In business for 10 years**
- **Top 500** – selected as one of the fastest growing companies in the US to be awarded *06/02*
- **"Weatherhead 100 - Outstanding Corporate Growth Award,"** Weatherhead School of Management 1999, 2000 and 2001
- **"Inner City 100 Award"** from Inc. Magazine's Initiative for a Competitive Inner City in 1999, 2000, and 2001

Adanced Real-Time Control Research

MAPPER (*Genetic Algorithm*)

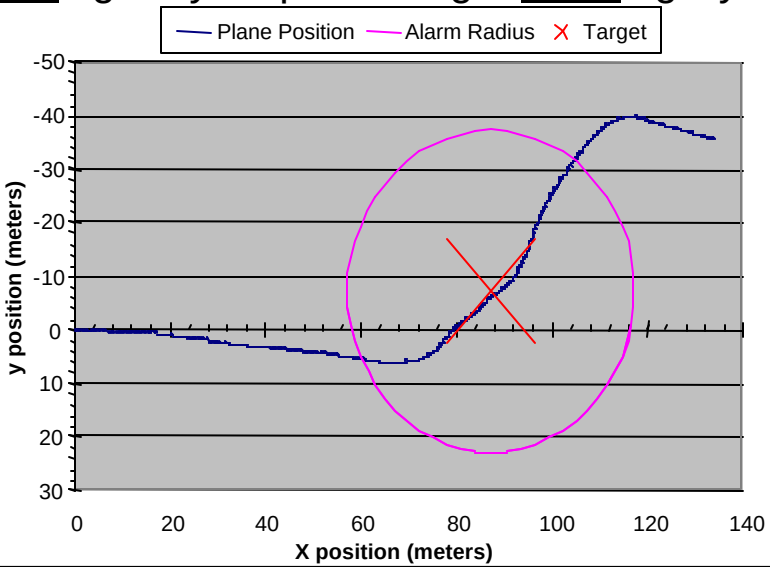
Multiresolution **A**utonomous **P**ath **P**lanning
Evolutionary **R**outing Algorithm

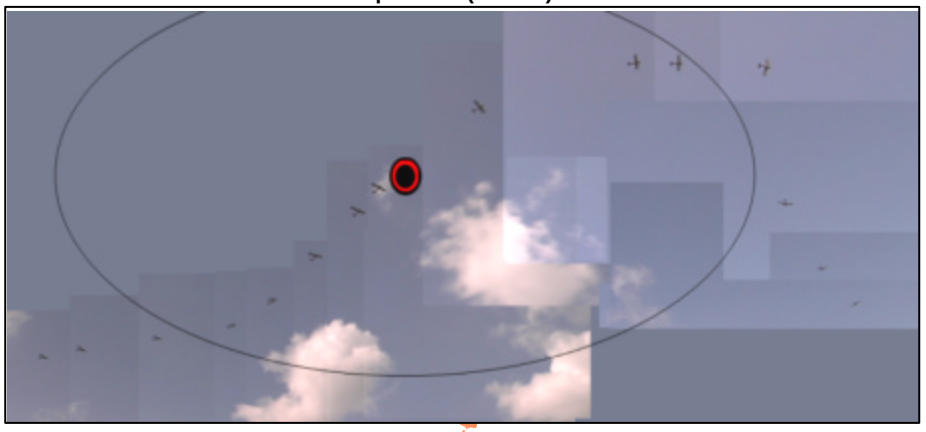


MAPPER - finds near optimal solutions

Biologically Inspired Controls

- **Bio**logically Inspired **A**utonomous **V**ehicle **E**scape **R**eflex **T**actic (***BioAVERT***)
- **Bio**logically Inspired Target **Seek**ing System

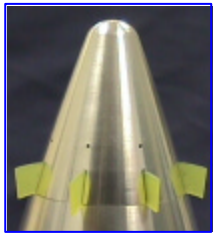


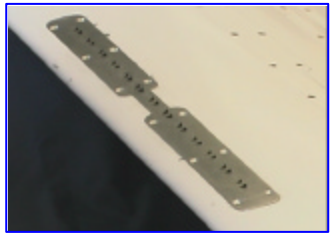


Micro Devices and Sensors

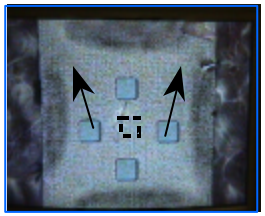
MEMS Microvalves

Flow Control Devices

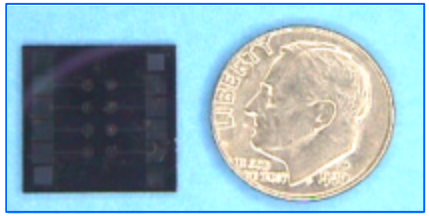




Missile and Airfoil Control



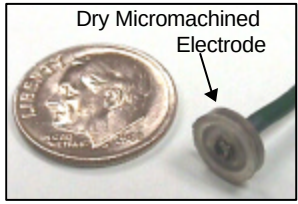
MEMS Microvalve



Array of 8 Microvalves

Medical Devices

Refreshable Braille Display System



Physiological Electrode

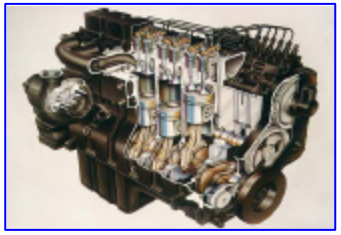
Micro Pressure Transducers

In-Situ Pressure Transducers for Turbine Engines

- dynamic pressure measurement
- Stall detection
- Reduced emissions

- Fuel efficiency
- Blade-tip passing
- Engine health monitoring
- Flame-out detection

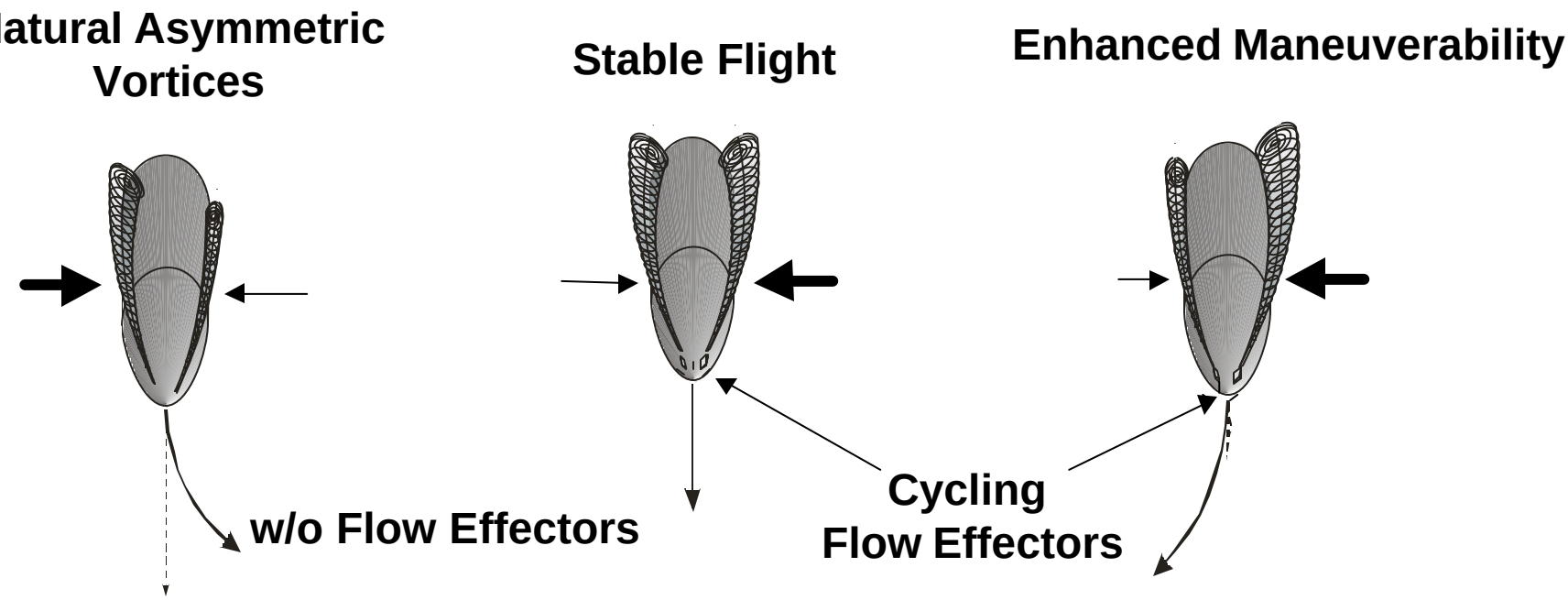
In-cylinder Pressure Transducers for Diesel Engines



- Linear output over wide range of strain
- High sensitivity
- Operates above engine temperature
- Robust design for combustion monitoring

Missile Control Theory

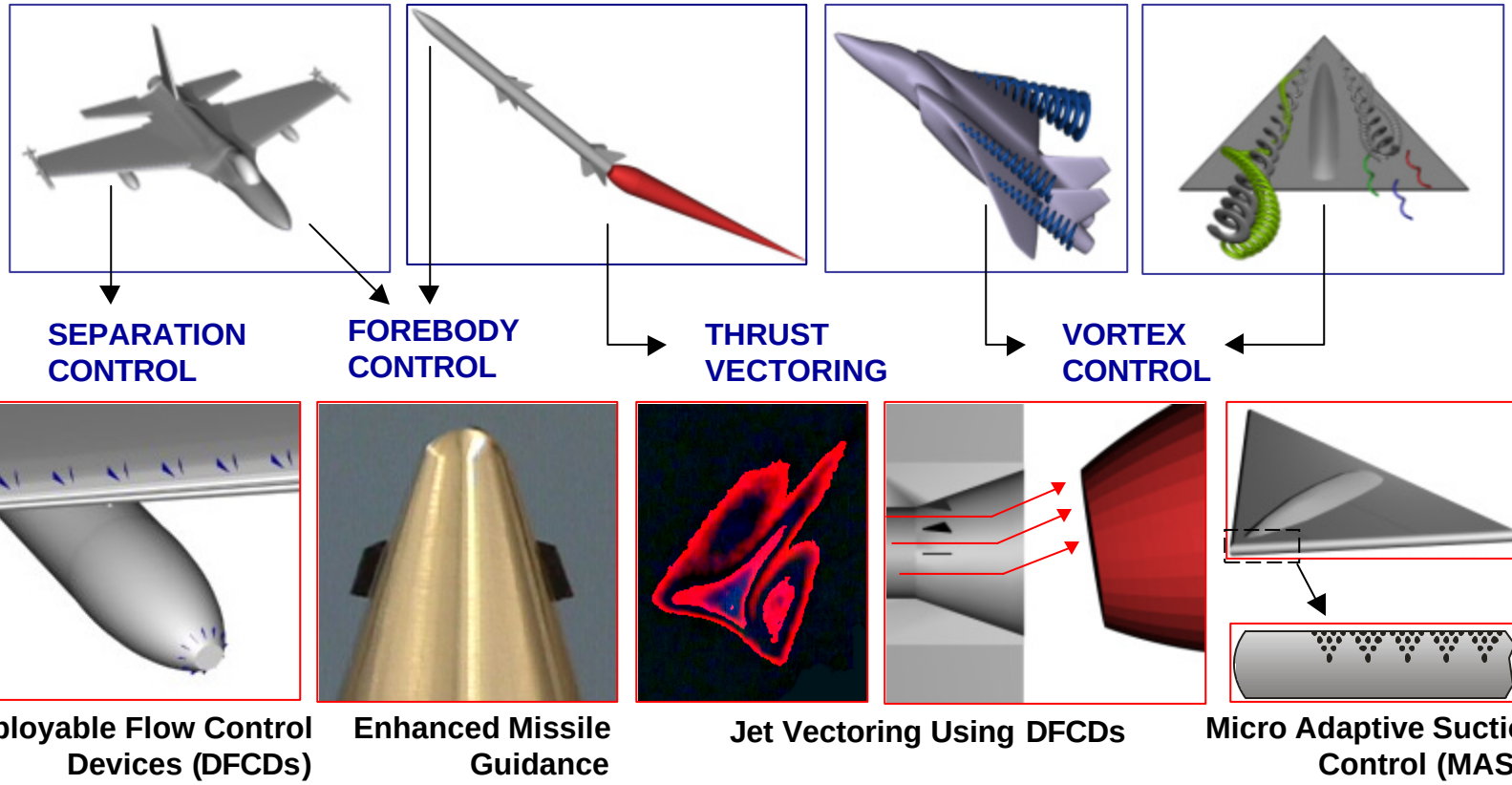
Enhanced Missile Maneuverability Through Intelligent Control of Asymmetric Vortices



Keys to Enhanced Maneuverability:

- **Real-time Controller** - respond to sensor feedback and guidance information
- **Pressure Sensors** - provide low cost flow environment characterization
- **MEMS Actuation** of Flow Effectors - provide low power, low volume actuation

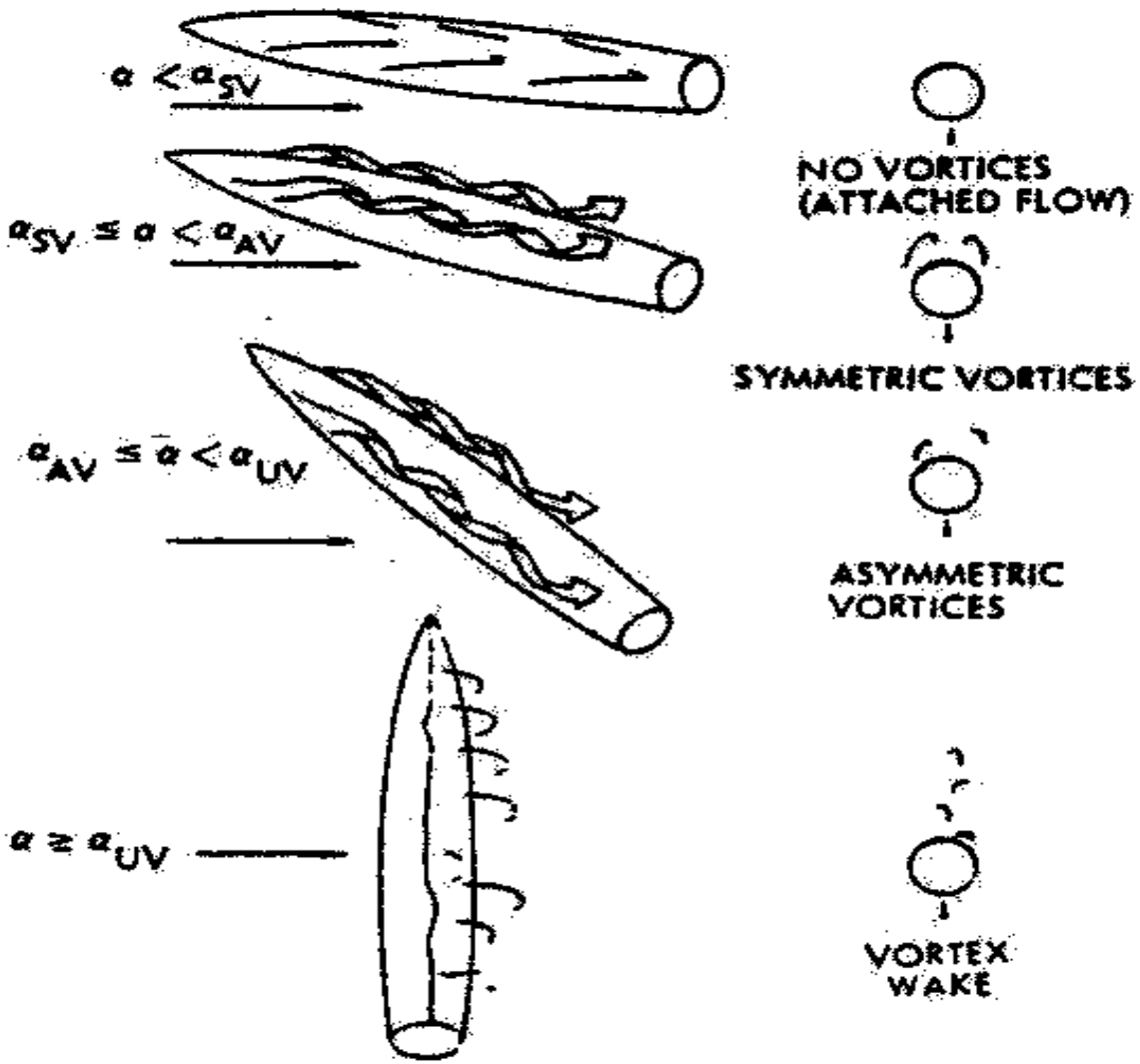
Active Flow Control Overview



- AIRFOIL RESEARCH
- DELTA WING RESEARCH
- MISSILE RESEARCH

→ Experimental Fluid Dynamics (EFD) + Computational Fluid Dynamics (CFD)

Asymmetric Vortices at High Angles of Attack



Effect of α on Leeside Flowfield

Asymmetric Vortex Shedding at High α is Caused By Uneven Flow Separation from the Nosecone

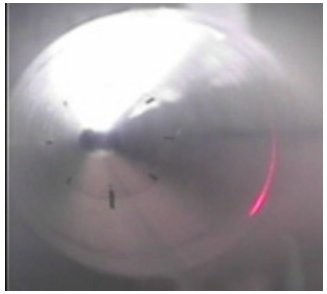
Reference:

Ericsson, L. E., Reding, J. P., *Asymmetric Flow Separation and Vortex Shedding on Bodies of Revolution*, Tactical Missile Aerodynamics, edited by Michael J. Hemsch, Vol. 141, Progress in Aerospace and Aeronautics, AIAA, New York, pp.391-452, 1991.

Slender Body Aerodynamic Problems

Significant Asymmetric Vortices at High Angles of Attack

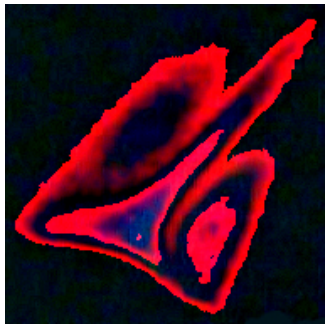
- **Limit Maneuverability and Range**
- **Reduce Stability especially at High Angles of Attack**



Missile Model

Causes of Asymmetric Vortices at High Angles of Attack

- **Uneven flow separation from the nosecone**
- **Micro-asymmetries on the surface of the nosecone**
- **Small dents, cracks in the paint, microscopic imperfections near the tip of the nosecone**
- **Other factors - bluntness of the forebody, Reynolds number, roll angle, and, the angle of attack.**

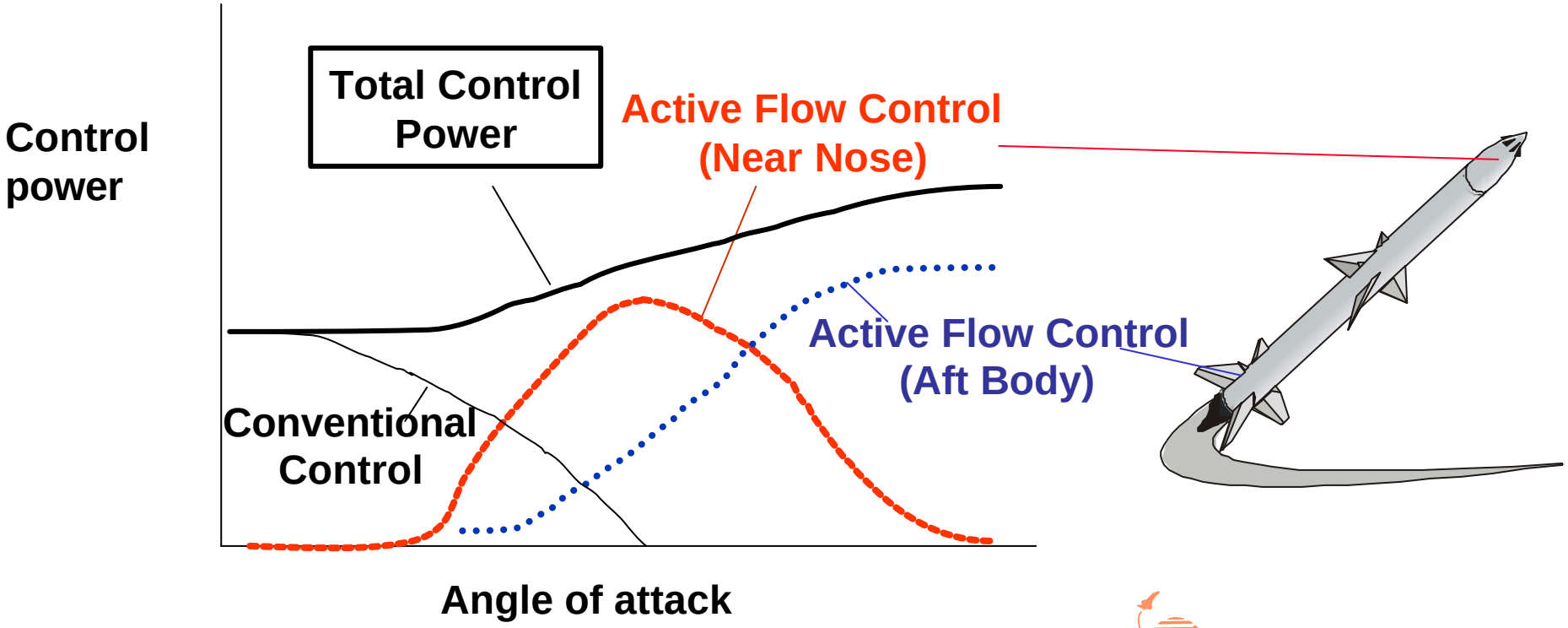


Flow Visualization using Laser Sheet

Significant yawing moments cause instability due to pressure differentials across missile body

Slender Body Research Goals

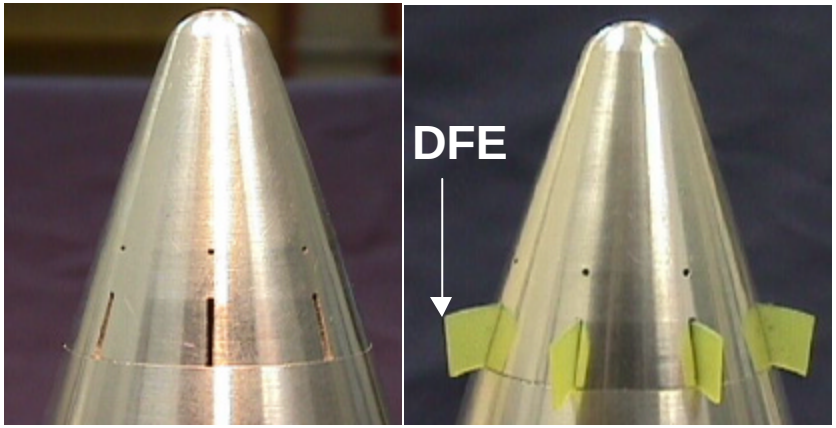
- **Stabilize a 3:1 Tangent Ogive Missile while at High Angle of Attacks by controlling Asymmetric Vortex Formation with Deployable Micro Flow Control Devices**
- **Generate Moments Utilizing Deployable Flow Effectors for Active Control**
- **Design and Develop a Control Algorithm based on Wind Tunnel Tests for Stabilization and Enhanced Maneuverability**



Deployable Flow Effectors –

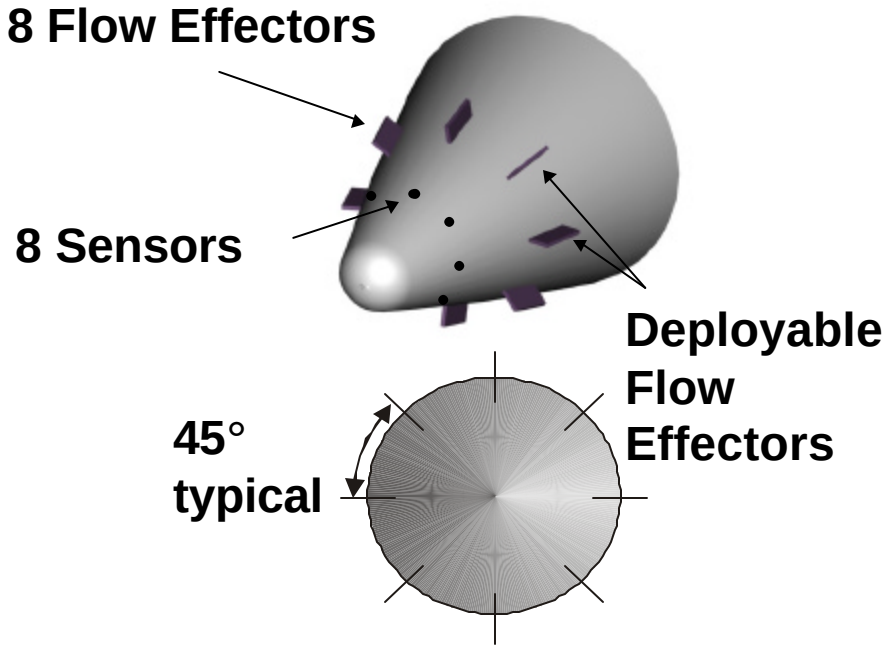
Co-Located Actuator and Sensors

Photograph of Nose



Retracted Flow Effectors

Flow Effectors Deployed



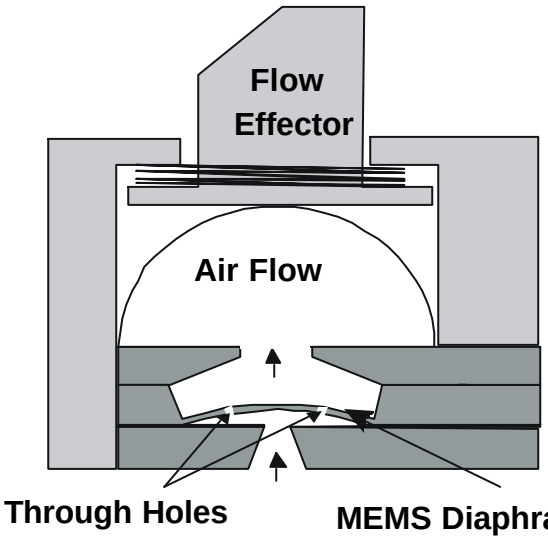
Goal to prove deployable flow effectors on missile nose can stabilize and control forces caused by phantom yaw at high alpha

MEMS Actuation for Deployable Flow Effectors

MEMS Challenges for aerodynamic surfaces

- **Need all weather Actuator (temperature, rain, snow, ice)**
- **The inherent fragility of the MEMS devices**
- **Insufficient throws**
- **Interfacing constraints such as power and size**
- **The temperature change (above 200°C)**

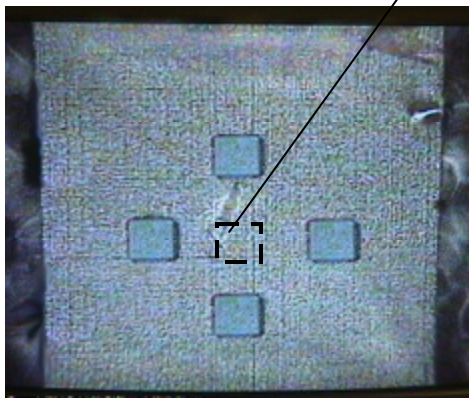
MEMS - Microvalve beneath the surface



ORI's Patented MEMS Microvalve Actuation

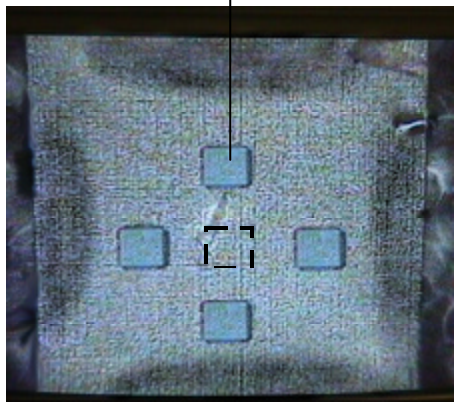
Power consumption < 5mW
Flow rates – 0-300 ml/min.
Pressure – 1-10 psi.

Orifice wafer thru holes



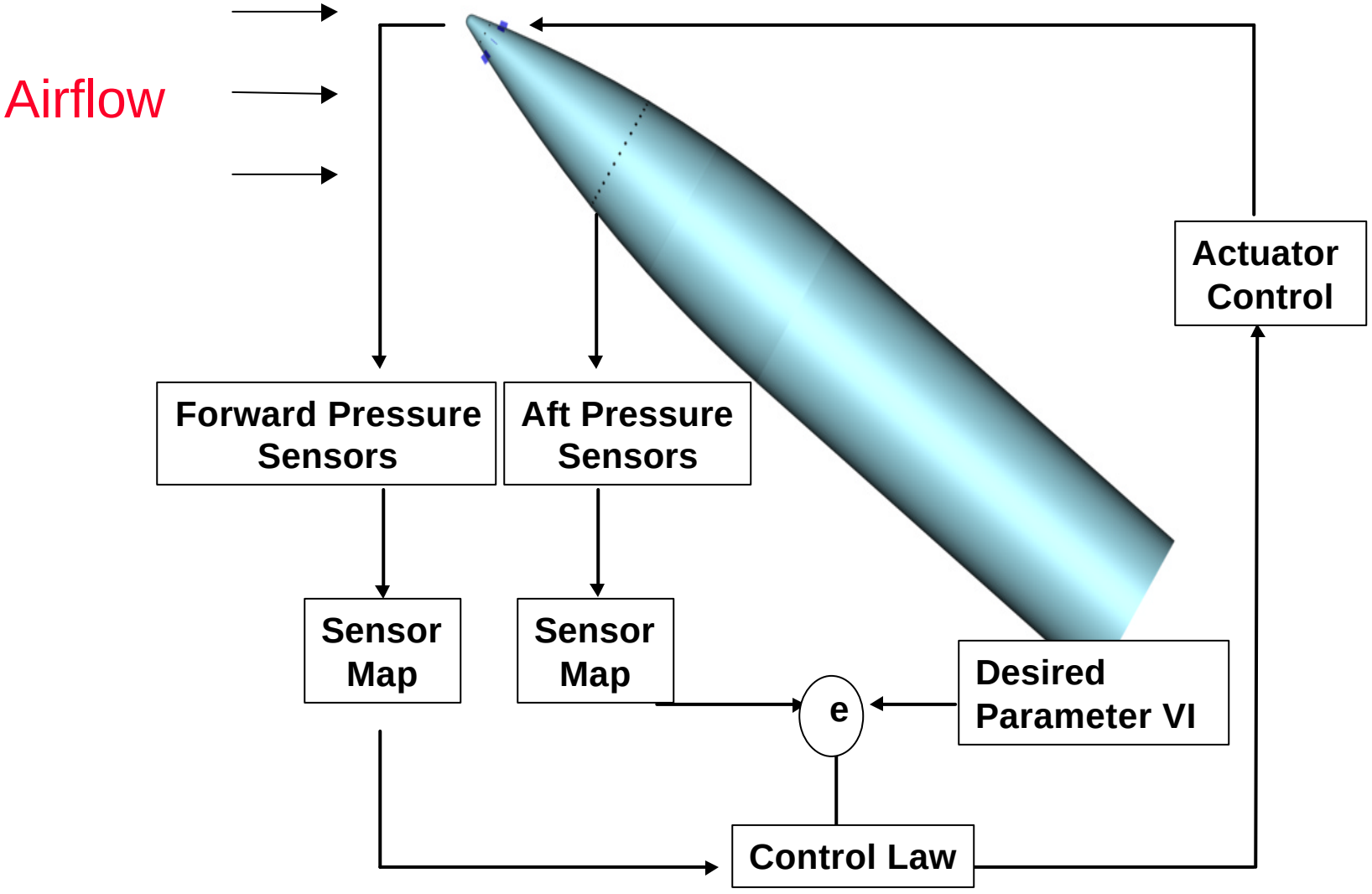
ORI's MEMS Microvalve – Closed position

Diaphragm wafer thru holes

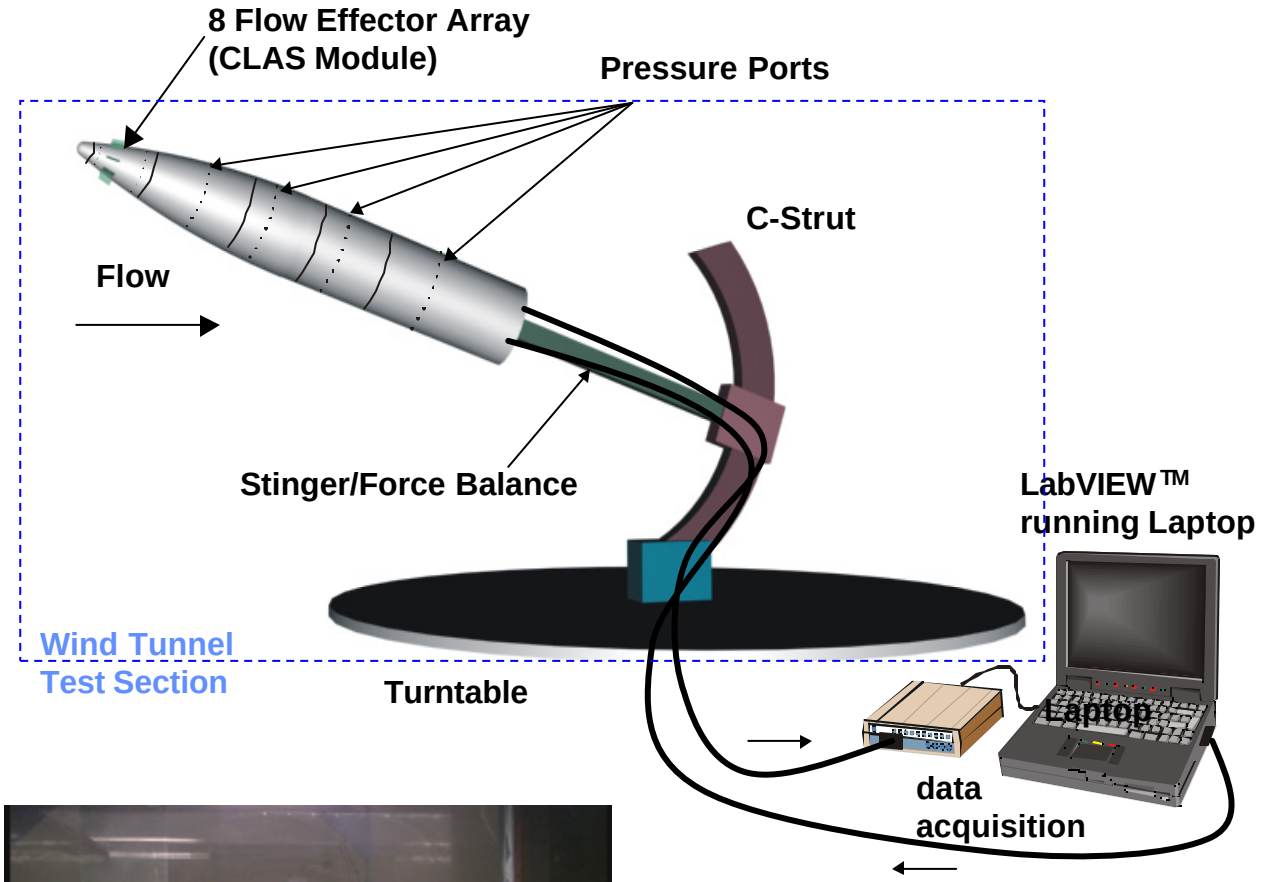


ORI's MEMS Microvalve – Open position

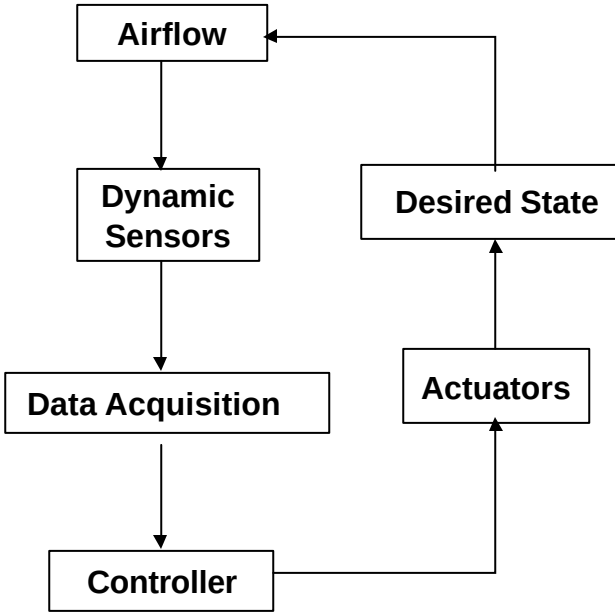
Closed-Loop Feedback Control – Block Diagram

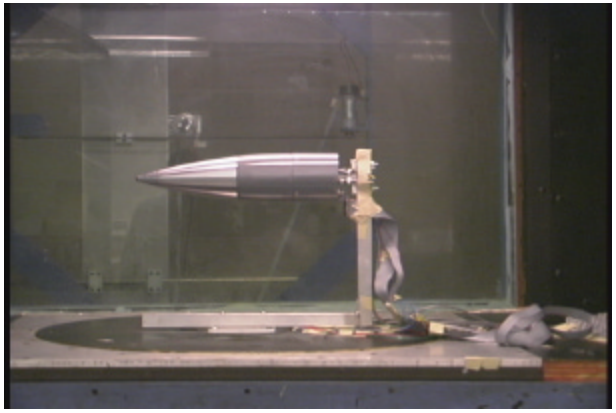


Experimental Set-up & Facility



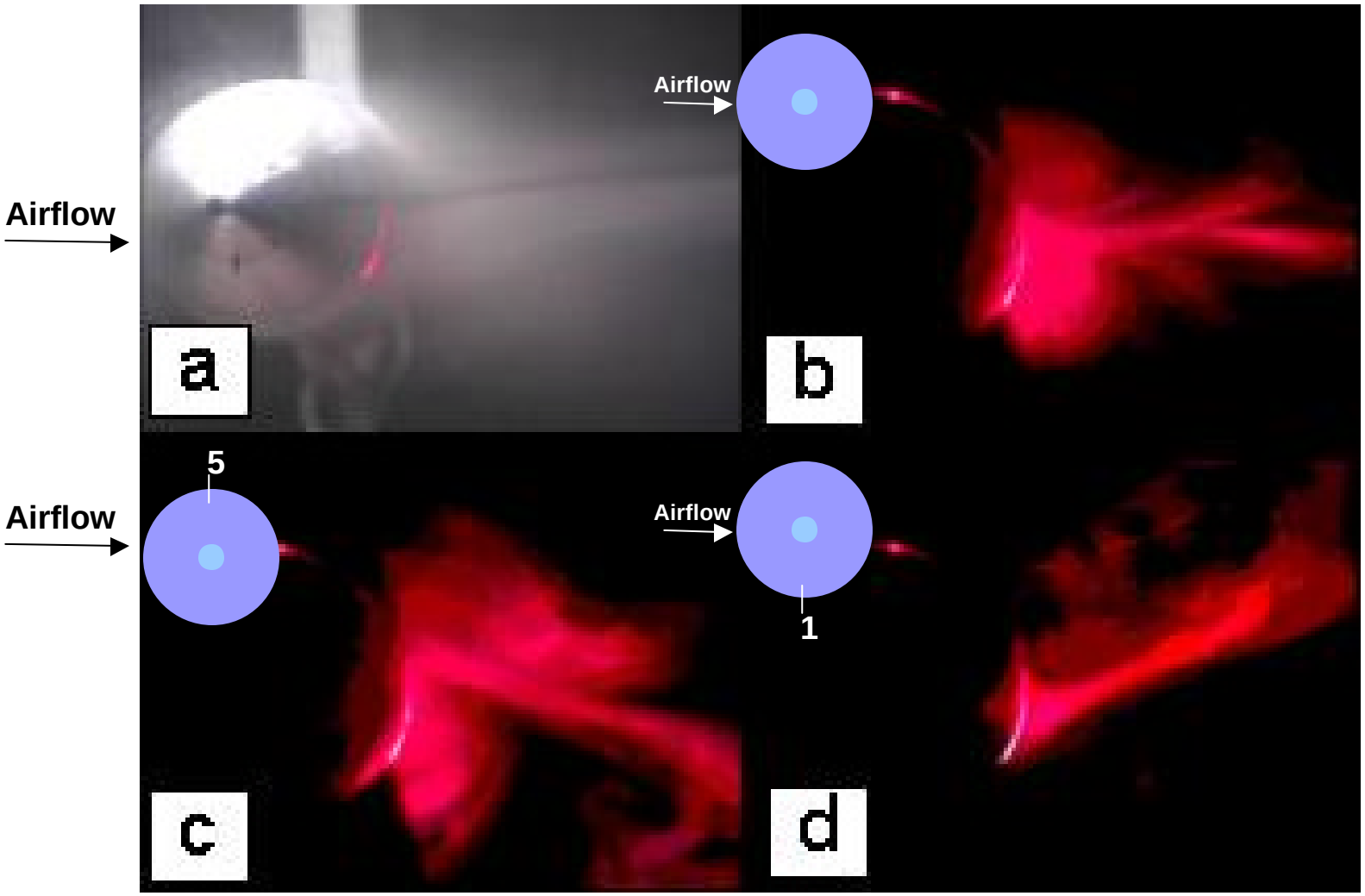
Controller Flow Chart





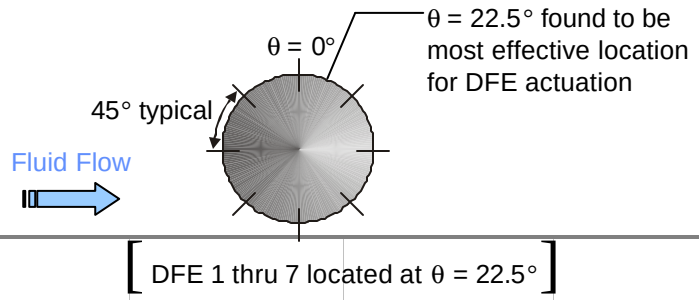
- **Wind Tunnel – 3 x 3 ft. (closed-loop) at The University of Toledo**
- **Reynolds No – 1 x 10^6**
- **AoA – 0°~60°**

Flow Visualization Snapshots - Vortex Control

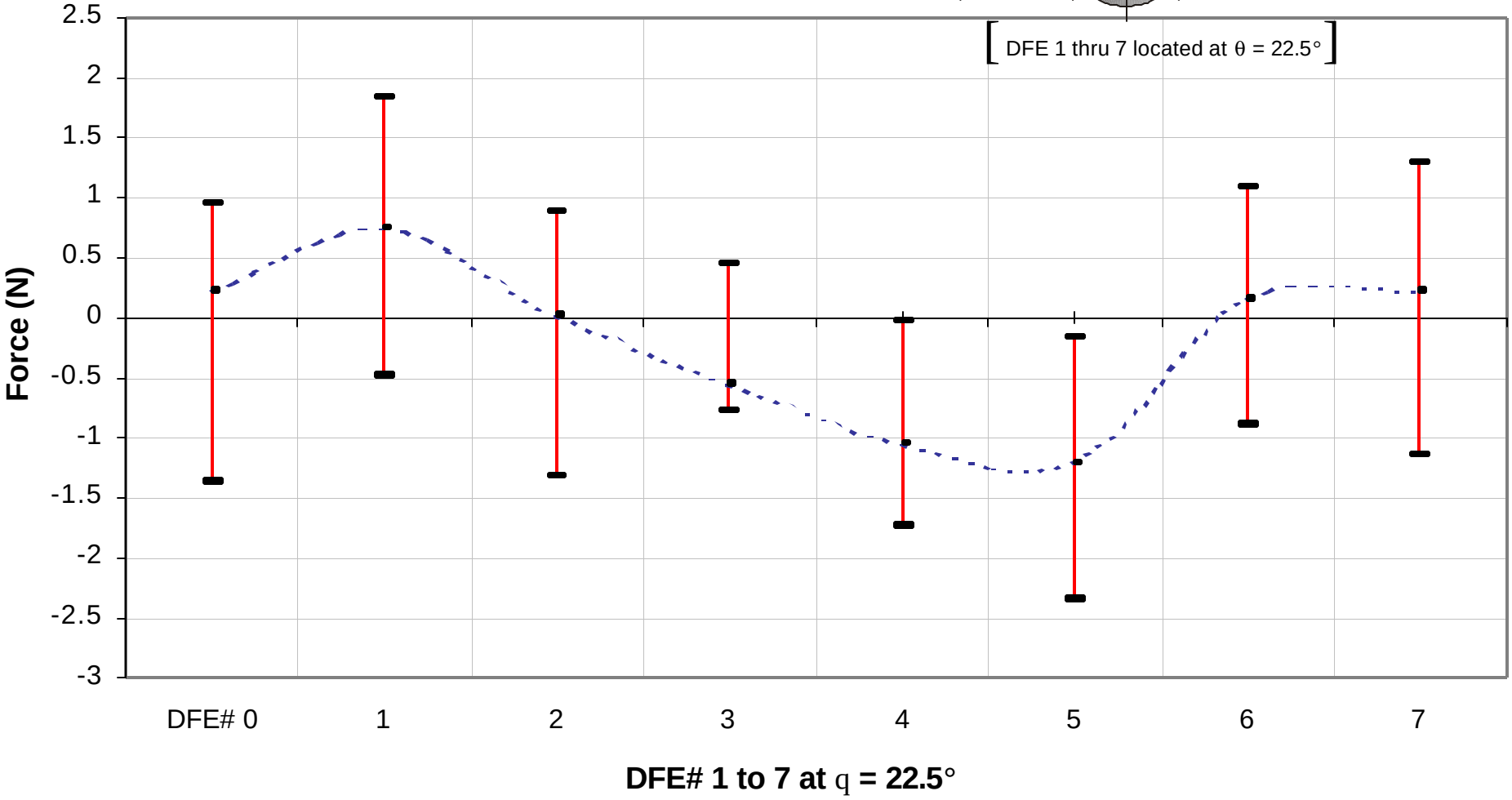


Laser sheet flow visualization at $\alpha = 60°$. (a) Normal view of Missile model (b) Baseline with no DFE (c) DFE #5 actuated (d) DFE #1 actuated.

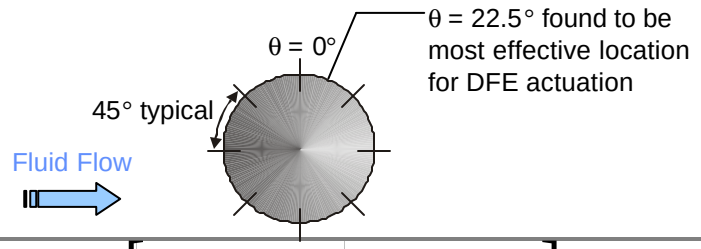
Experimental Results - Control Forces at 40° AoA



Net forces generated at pitch 40° - Yaw 0°

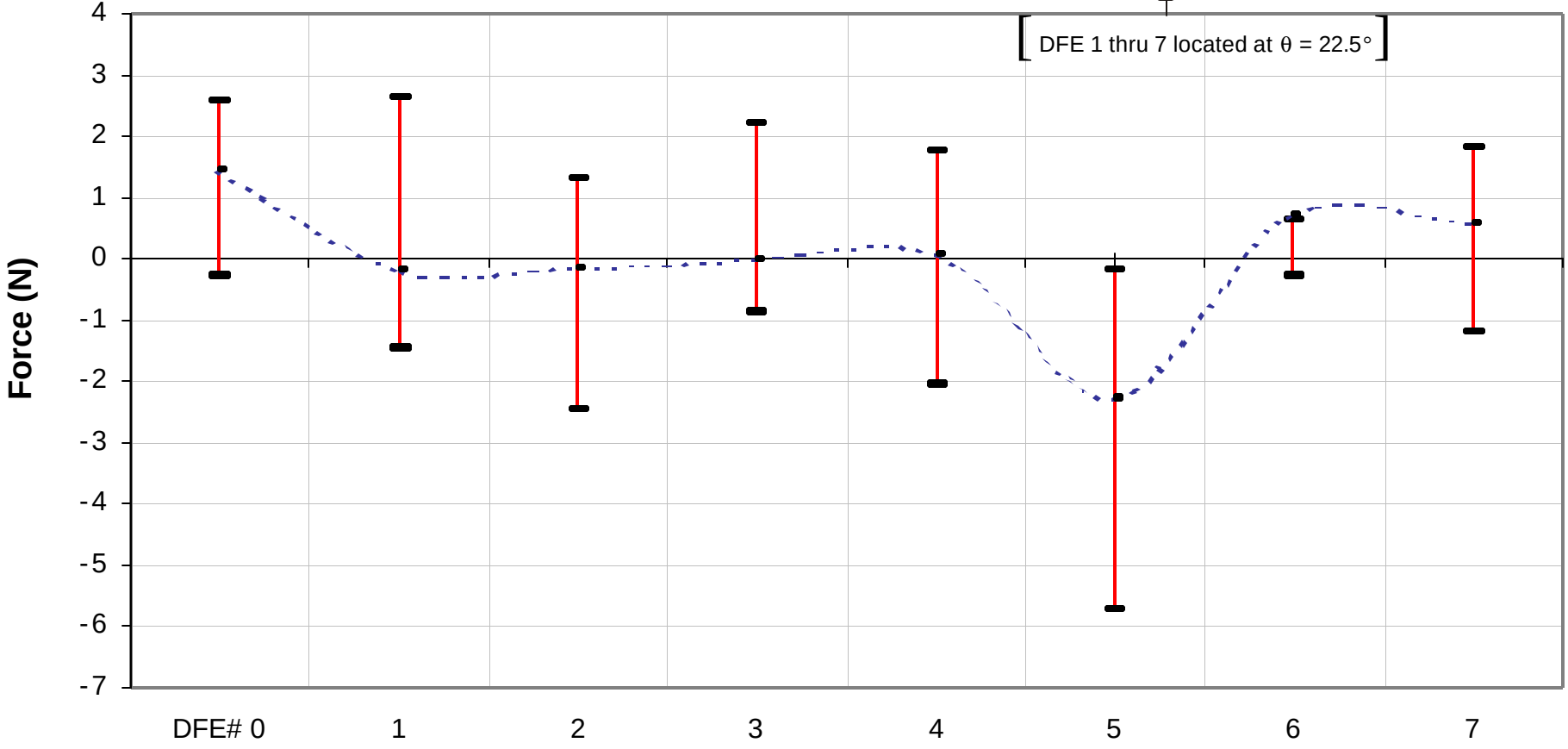


Control Forces - 45° AoA



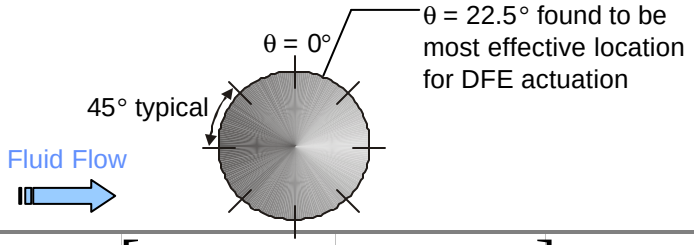
Net forces generated at pitch 45° - Yaw 0°

DFE 1 thru 7 located at θ = 22.5°



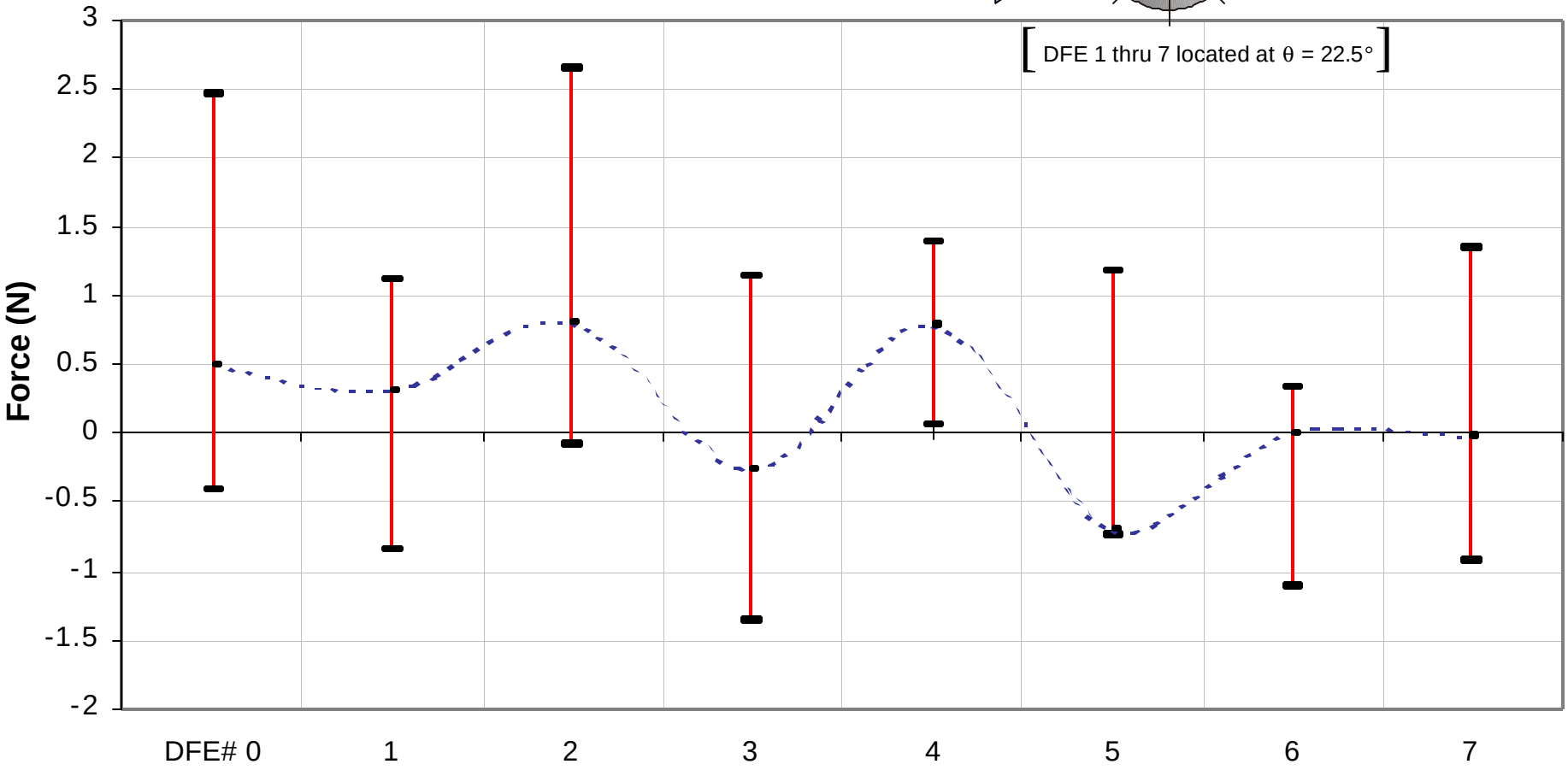
DFE# 1 to 7 at q = 22.5°

Control Forces - 50° AoA



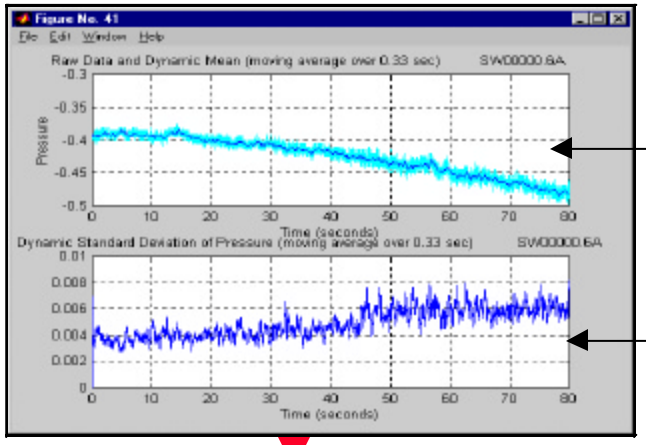
Net forces generated at pitch 50° - Yaw 0°

[DFE 1 thru 7 located at θ = 22.5°]



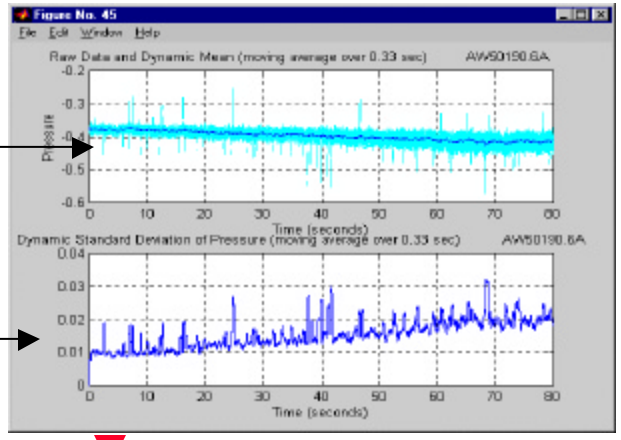
DFE# 1 to 7 at q = 22.5°

Deployable Flow Effectors Cycling Effects



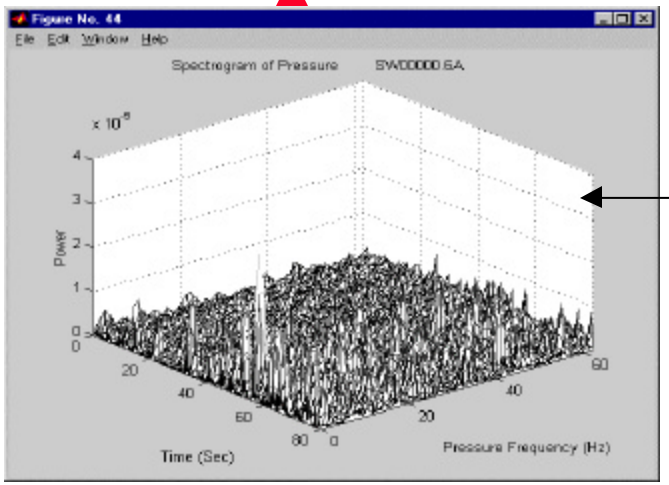
Pressure and its dynamic mean vs. time

STDEV vs. time

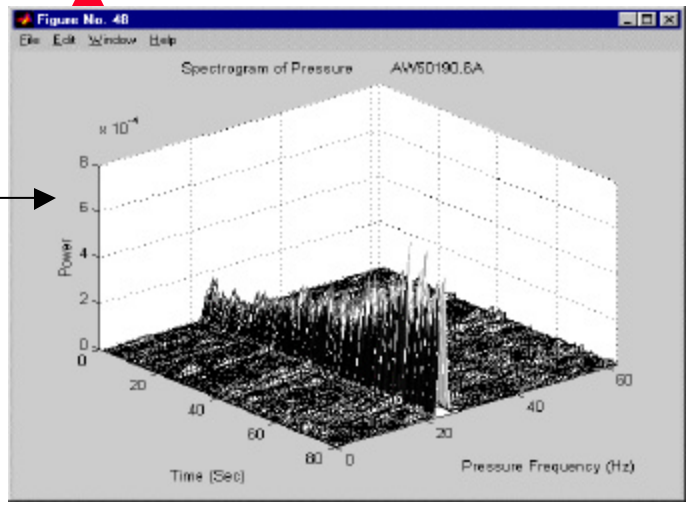


Constant DFE Deployment

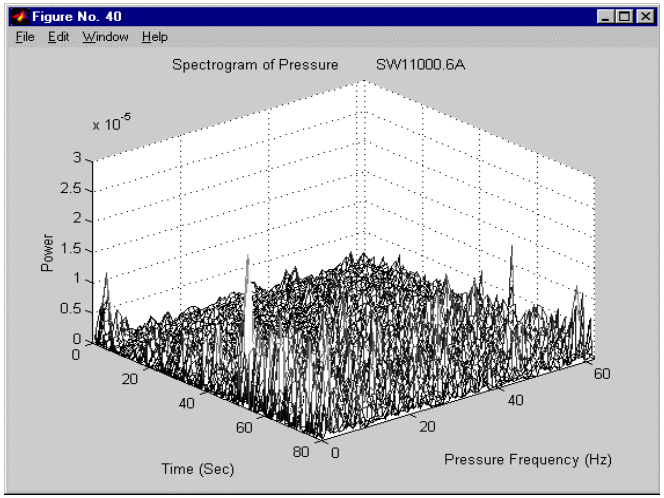
DFE Deployed at 20 Hz. with a 50% duty cycle



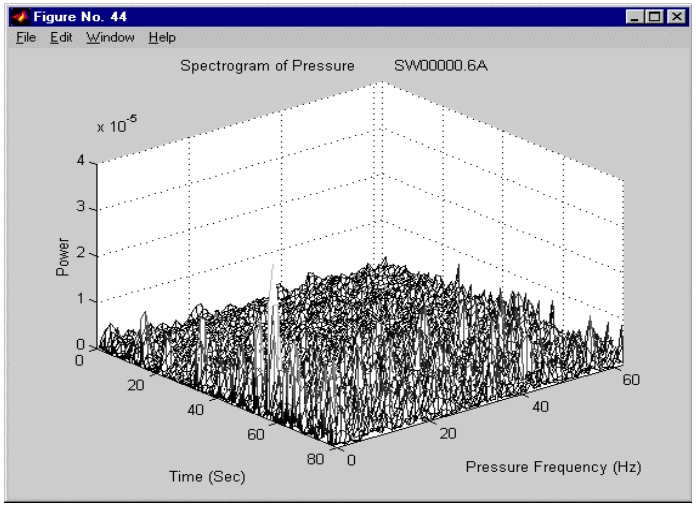
Time varying spectral plots



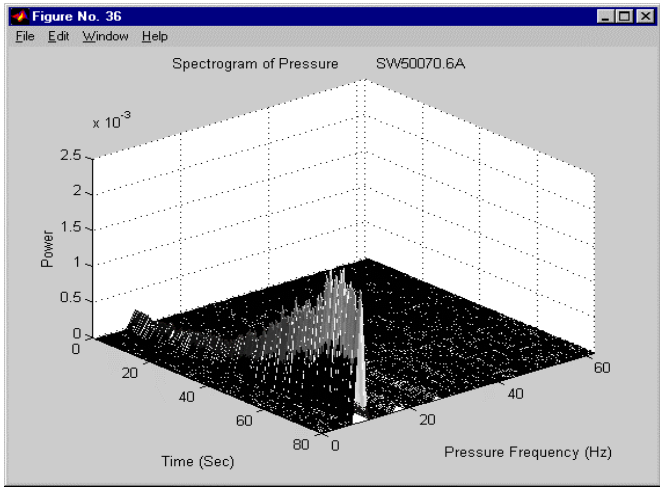
Deployable Flow Effectors – Power Spectrum



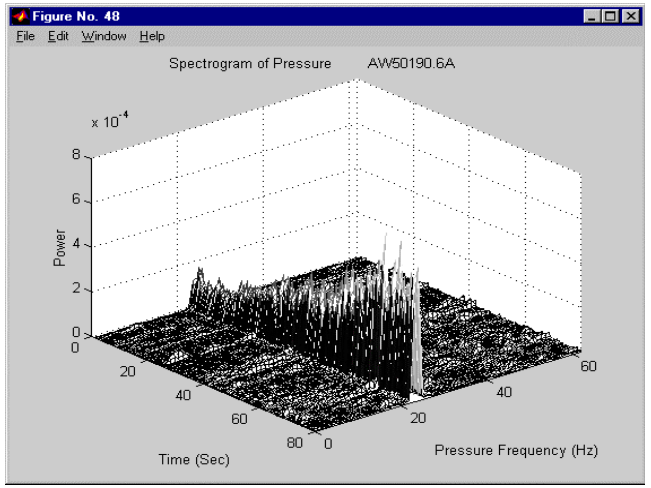
Power spectrum baseline model



Power spectrum – passively deployed flow effector

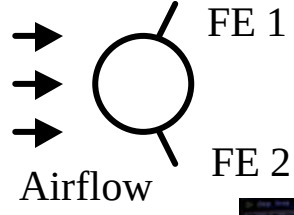


Power spectrum – DFE cycling at 7 Hz. 50% duty cycle



Power spectrum – DFE cycling at 20 Hz. 50% duty cycle

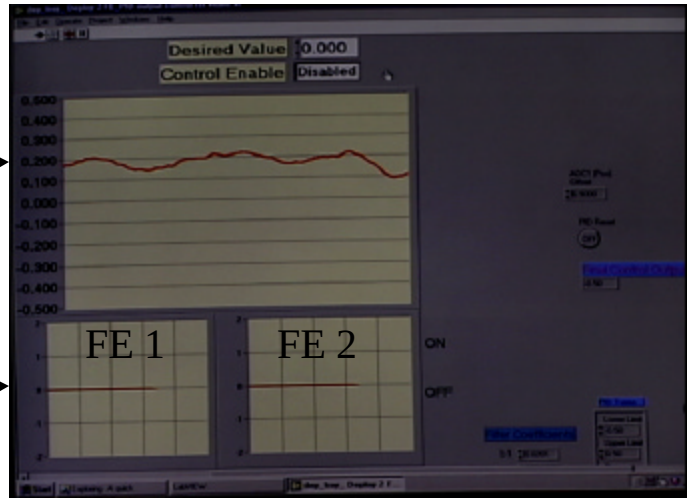
Real-Time Dynamic Missile Control @ 60° AoA



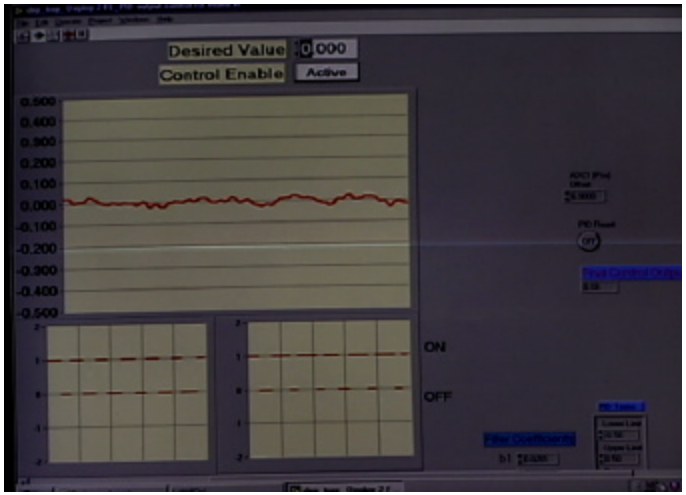
Base Line (No Control)

Real Time Force Plot

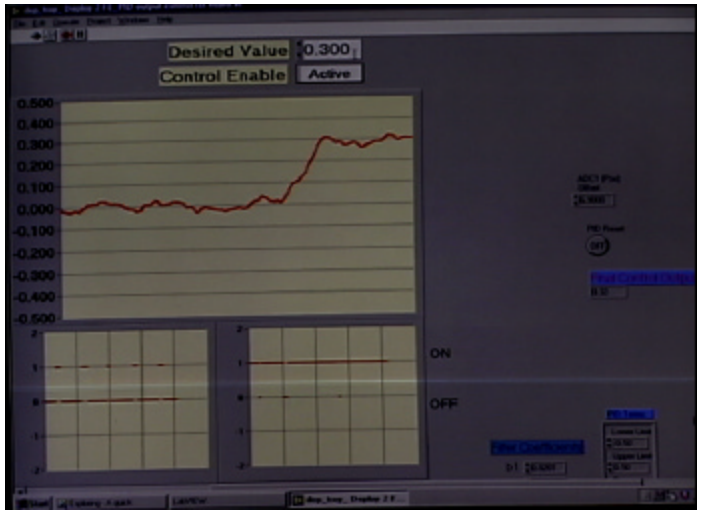
Actuator State



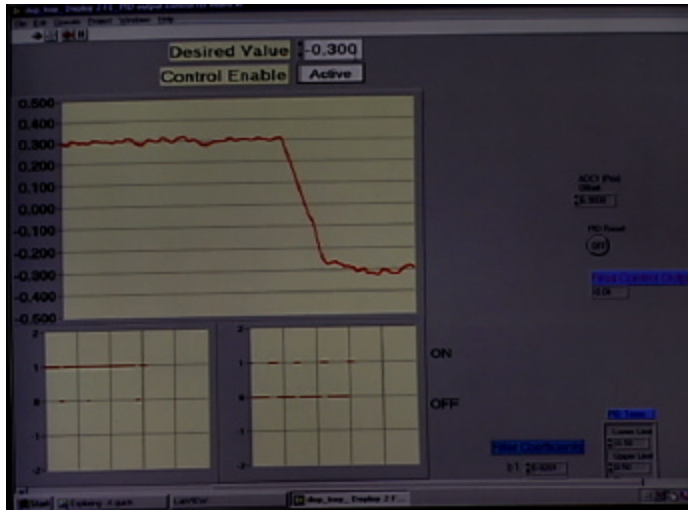
Control Enabled (Zero Side Force)

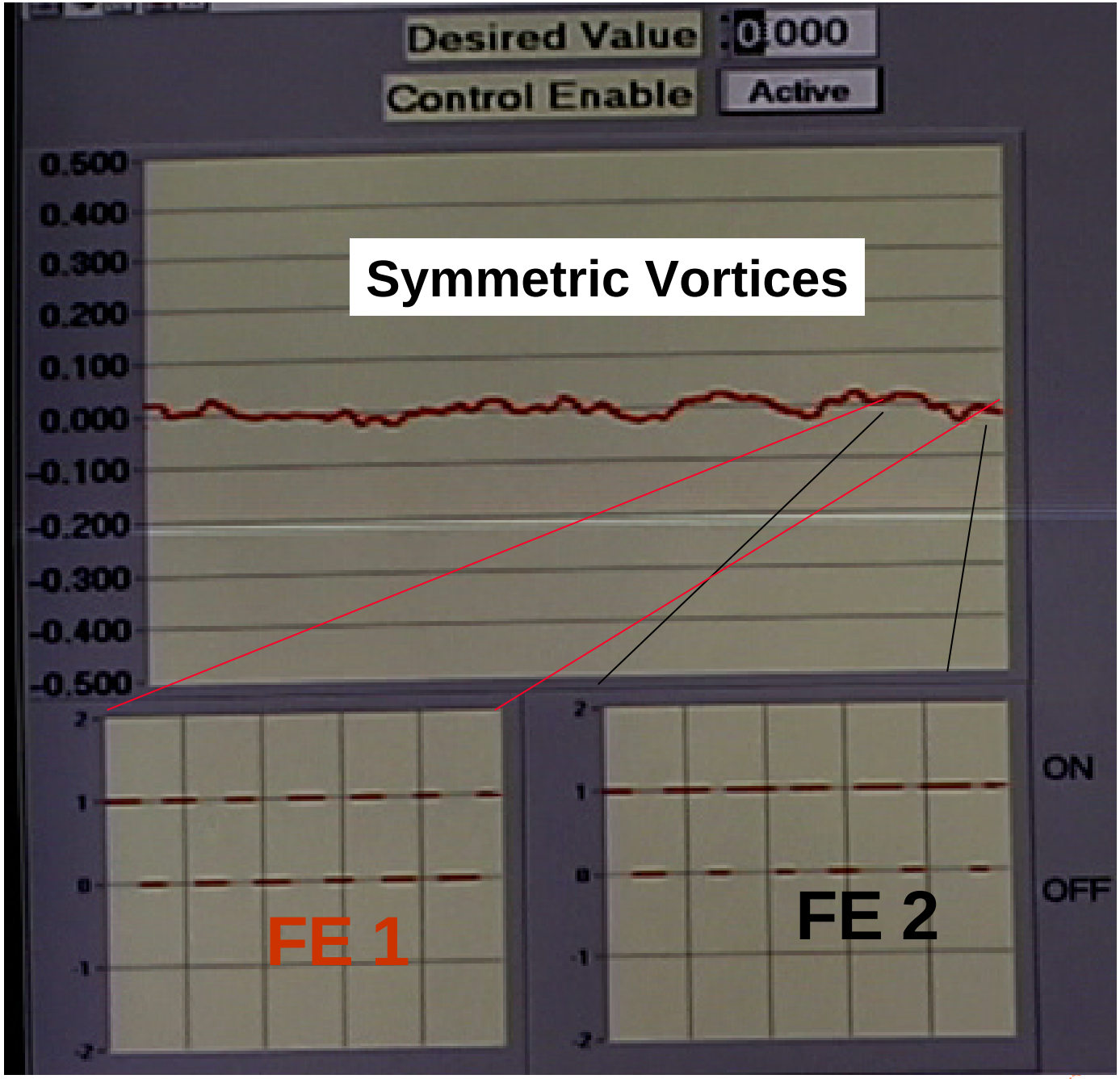


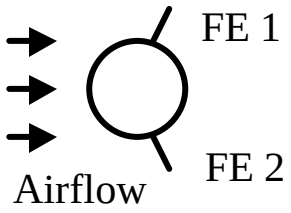
Control Enabled (Desired Force Obtained)

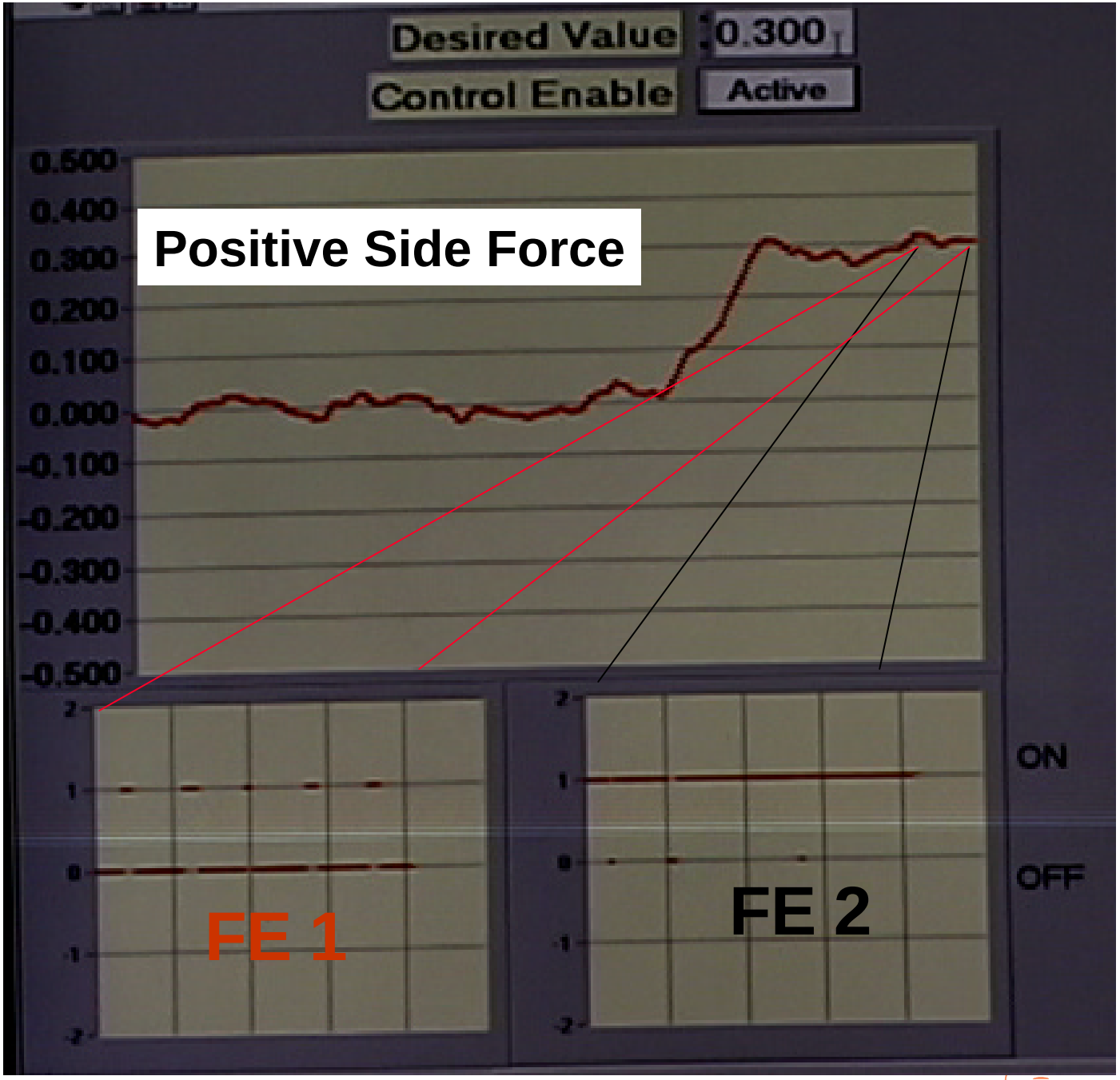


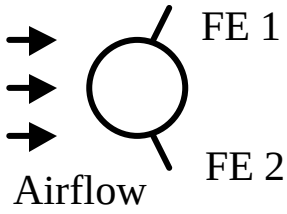
Control Enabled (Opposite Side Force Obtained)



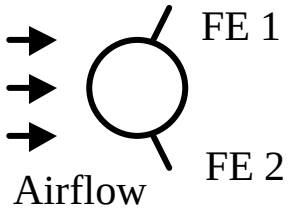

Desired Value
0.000
Control Enable
Active
0.500
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
Symmetric Vortices
2
1
0
-1
-2
FE 1
FE 2
ON
OFF


FE 1
FE 2
Airflow


Desired Value
0.300
Control Enable
Active
0.500
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
Positive Side Force
FE 1
FE 2
ON
OFF

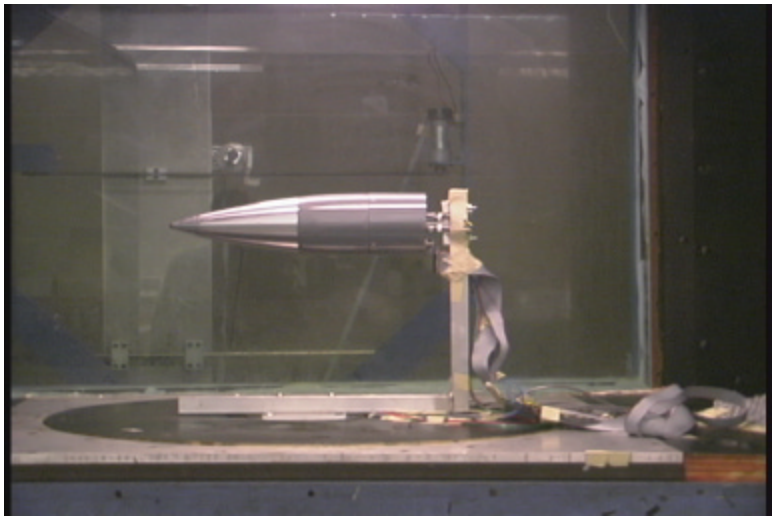

FE 1
FE 2
Airflow

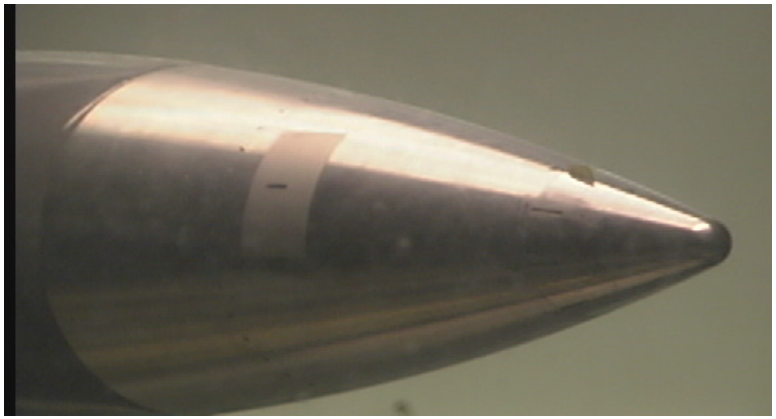

Desired Value
-0.300
Control Enable
Active
0.500
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
Negative Side Force
FE 1
FE 2
ON
OFF


FE 1
FE 2
Airflow

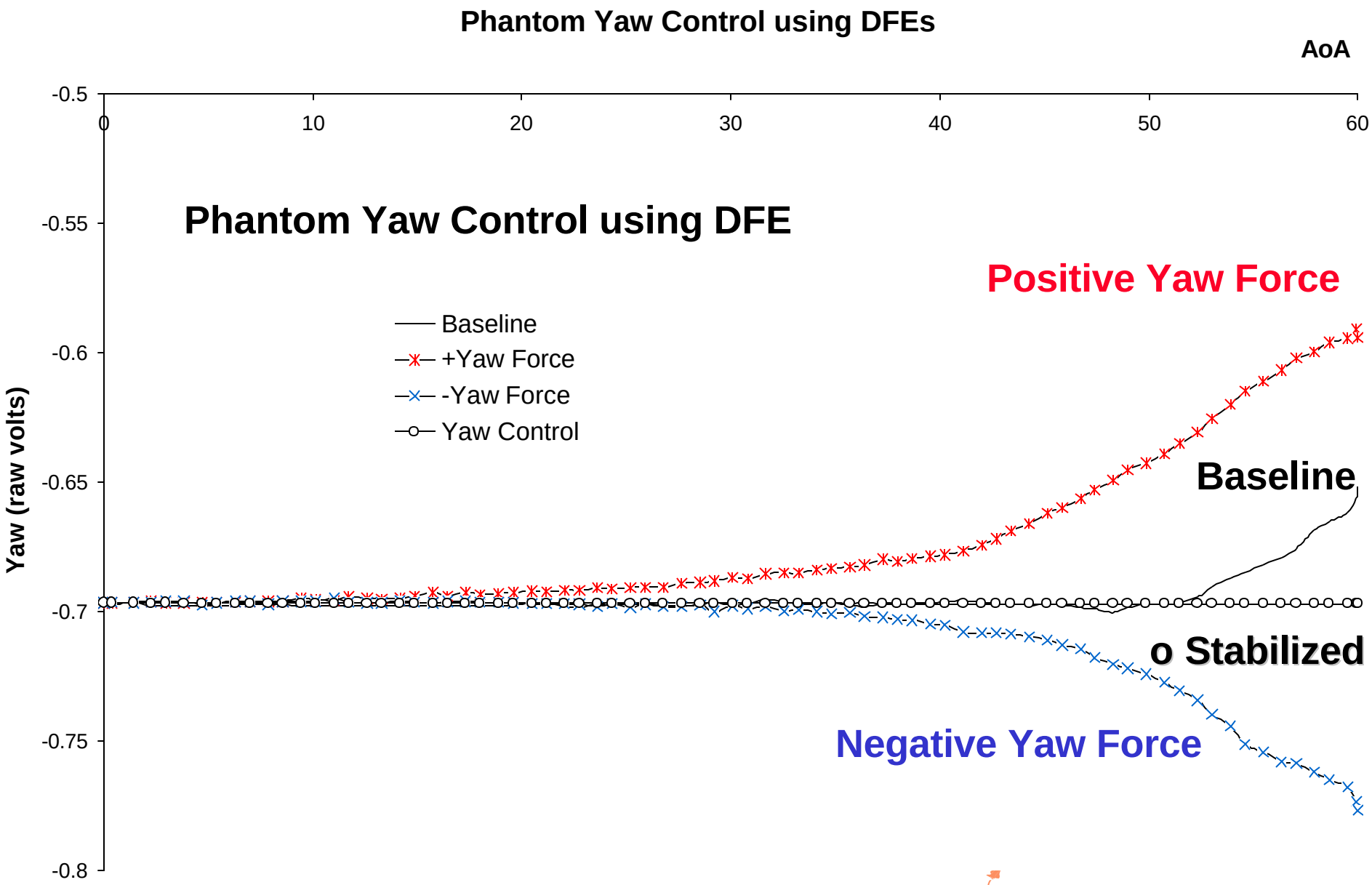
Dynamic Model Testing

- **Pitch Rates up to 140°/s**
- **Dynamic Missile Control with Multiple Flow Effectors and Pressure Sensors**
- **Closed Loop Control During High Rates**





Dynamic Sweep & High Alpha Missile Control

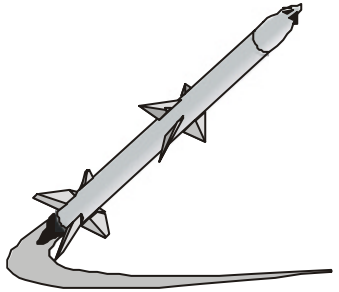


Accomplishments of Missile Control Program

- Stabilized a 3:1 Tangent Ogive Missile model while at High Angle of Attacks Using Co-located Sensors and Actuator which controlled Asymmetric Vortex Formation with Deployable Flow Control Devices

- Successfully Generated Moments Utilizing Deployable Flow Effectors for Active Control

- Demonstrated Closed-loop Missile Control Under Static Conditions, High Alpha Sweep, & Dynamic Conditions at High Alpha During Wind Tunnel Tests



Asymmetric Vortex Shedding

Symmetric Vortex Shedding